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Unsplit Hydro in EAP Codes

Josh Dolence

*Team: J. M. Campbell, A. B. Isner, S. W. Jones,
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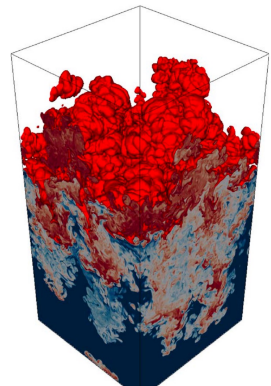


June 9, 2021

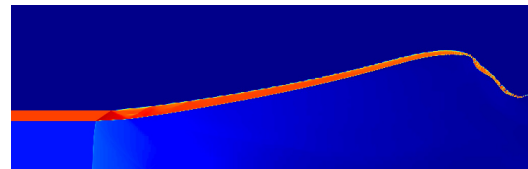
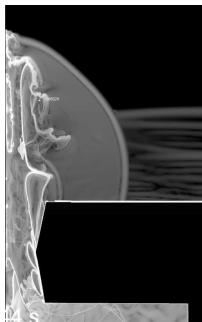
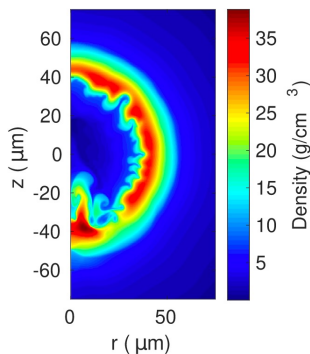


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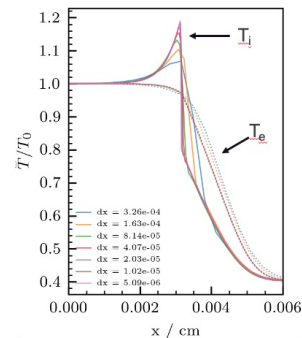
Hydro in EAP Codes



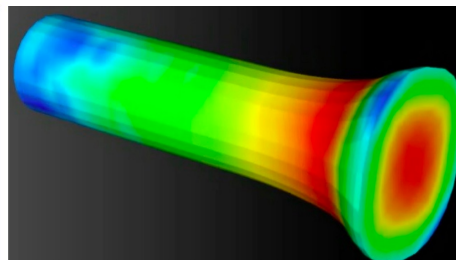
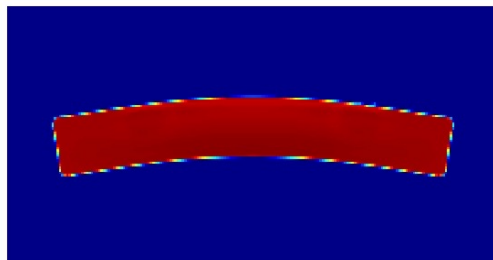
Gases, liquids, and collisional plasmas



“Advection” for other physics packages

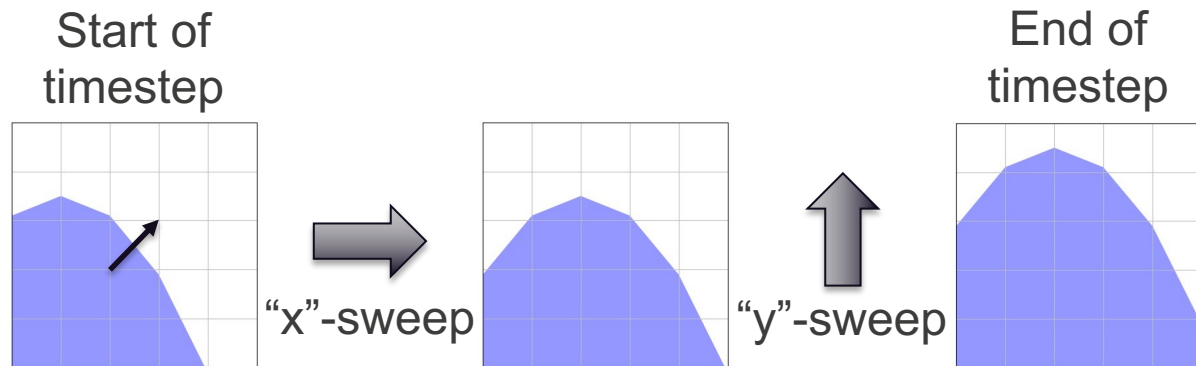


Solids, including the evolution of internal stresses

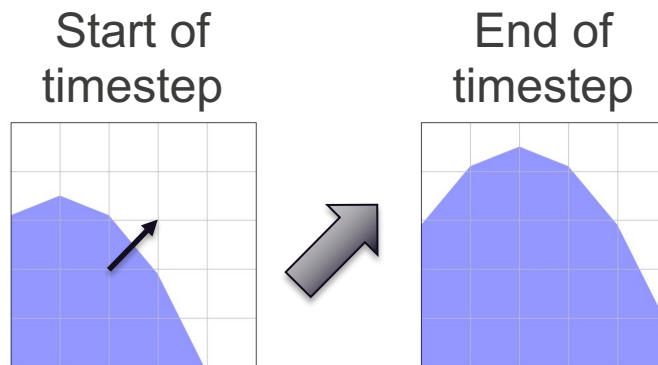


What is “Unsplit” Hydro?

Other options in EAP codes use **directional splitting**



Unsplit hydro is **directionally unsplit** (updates in all directions simultaneously).



Motivations

- Directional splitting thought to cause problems
 - Symmetry
 - Solid Mechanics
- Directional splitting definitely does have limits
 - MHD
- Other hydro solvers in EAP codes are unique
 - Forced isolation from the rest of the hydrodynamics community
 - Only a few people in the world *really* understand the method and its special sauce
 - Onboarding new scientists slow

What is Unsplit Hydro?

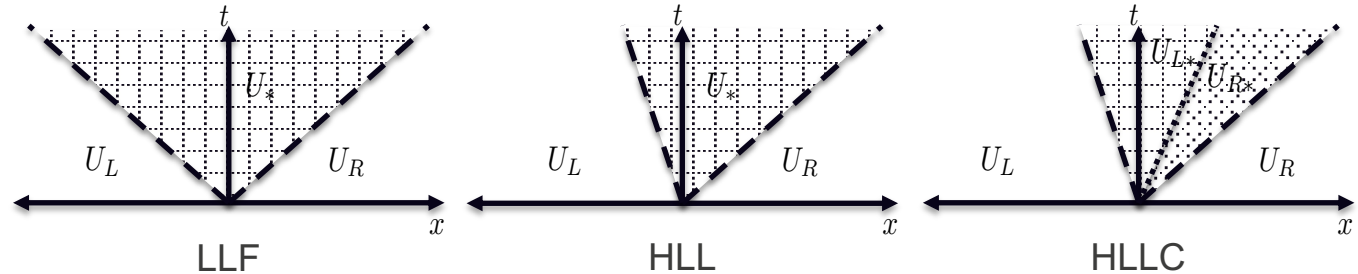
- Basic scheme is a “**finite volume, direct Eulerian, directionally unsplit, higher-order Godunov-type**” hydro that uses the “**method of lines**”
- **Finite volume** – Evolve cell-averaged quantities
- **Direct Eulerian** – No mesh motion, real or imagined
- **Higher-order** – Cell-averaged quantities are reconstructed with polynomials to better approximate the state as needed
- **Godunov-type** – Riemann problems are solved to define intercell fluxes
- **Method of lines** – A generic and powerful approach to evolving PDEs by discretizing space and using well-developed ODE solvers

“Default” and “Unsplit” hydrodynamics solvers are very different, even in 1D.

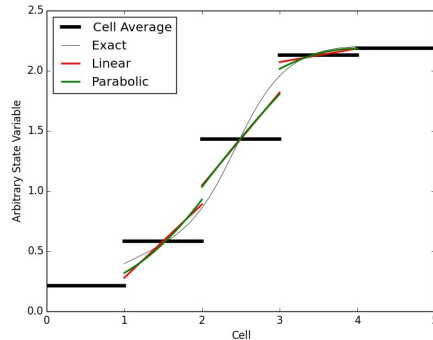
Unsplit Hydro Key Ingredients

Three core components have options that control accuracy/stability.

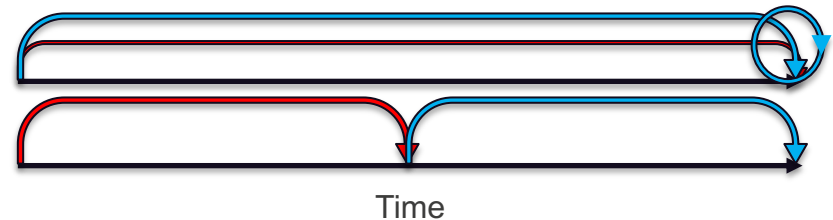
Riemann Solvers



Reconstruction

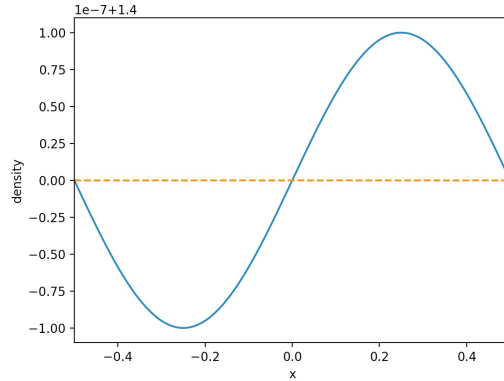


Time Integration

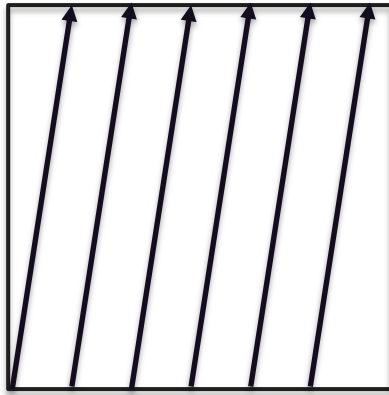


Extensible to incorporate future improvements!

Linear Acoustic Modes: A Basic, but Powerful Test of Correctness



In 1D we model a **single** wavelength on a periodic domain

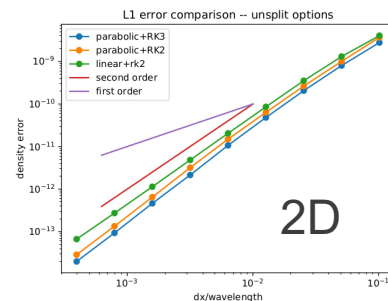
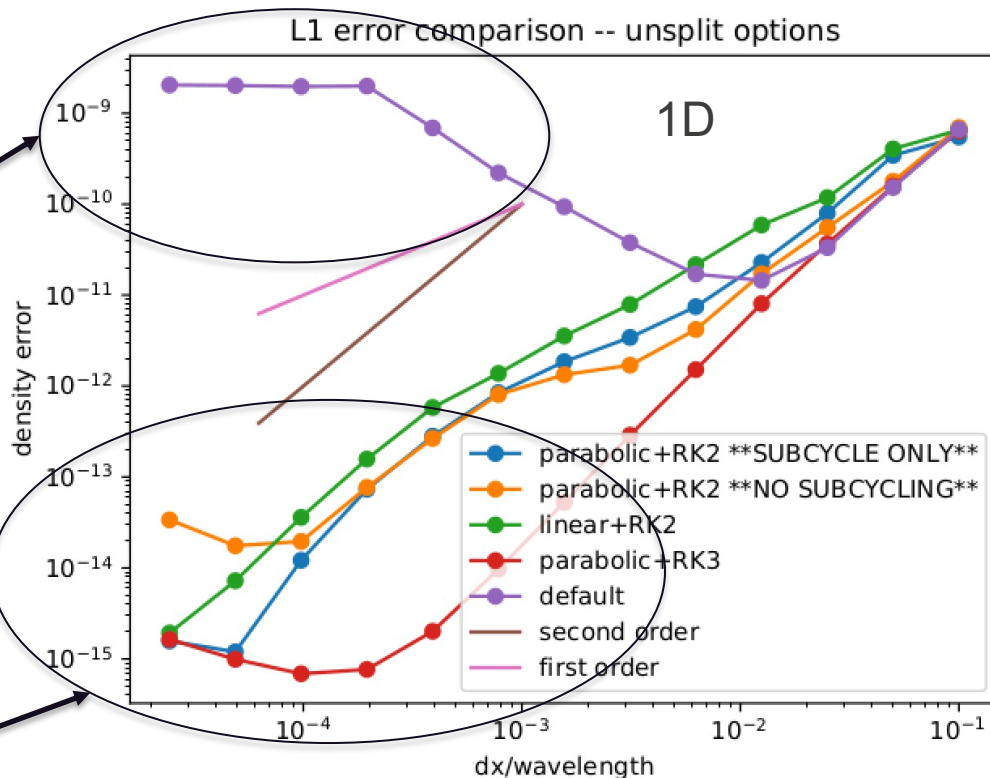


In 2D and 3D, we rotate the setup to follow the multidimensional evolution

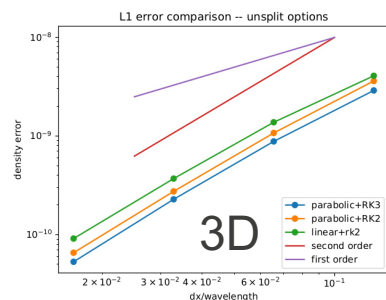
Unsplit Hydro is implemented correctly

A small inconsistency is revealed in default hydro

Unsplit Hydro options converge to machine precision



Unsplit Hydro converges as expected in multi-D

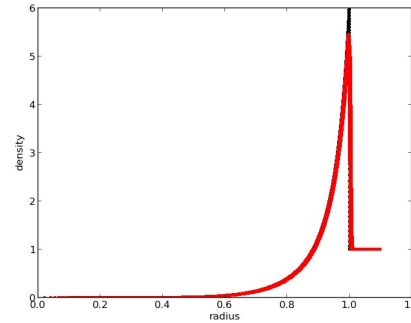


Sedov Explosion: A Classic Test for Symmetry and “Carbuncles”

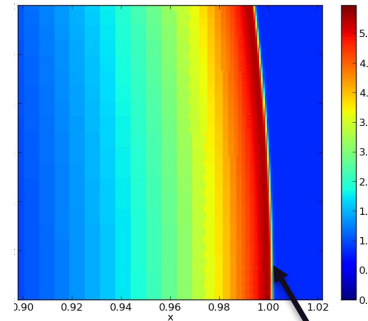
A spherically symmetric
blast wave



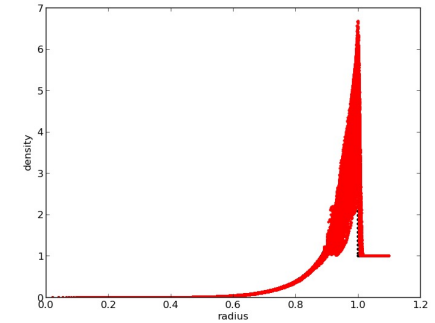
**Unsplit preserves symmetry
much better than Default
and suppresses the
Carbuncle**



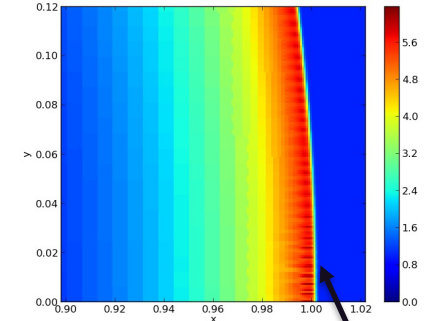
Unsplit



No Carbuncle



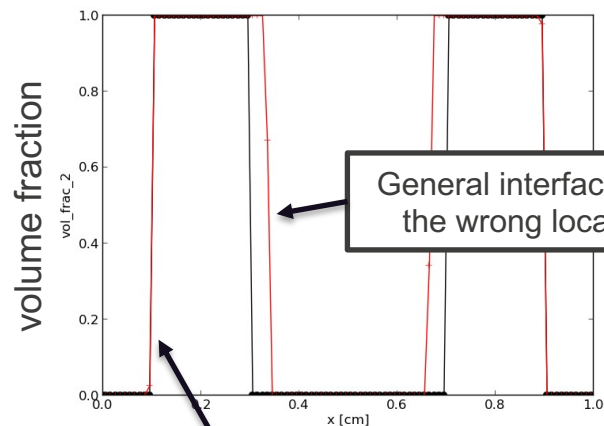
Default (split)



Carbuncle

Material Interface Advection: A Simple Test of Numerical Mixing and Interface Position

- Default Hydro has the option of using the VOF method to maintain sharp interfaces
- Unsplit Hydro does not have a sharp interface scheme yet

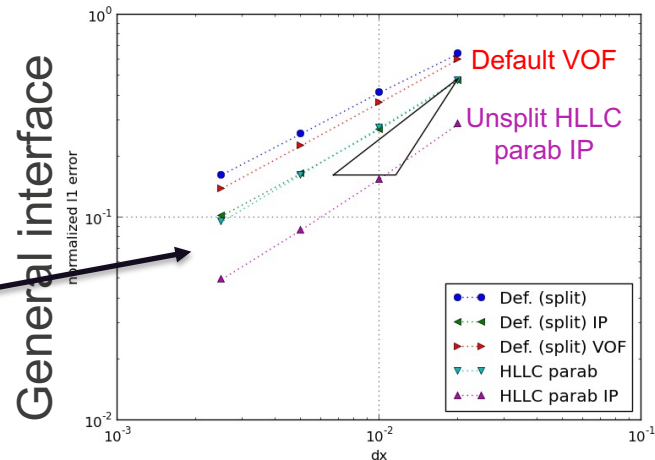
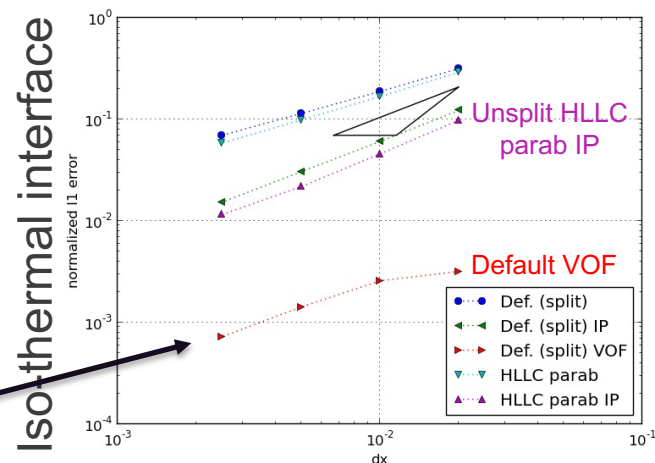


Iso-thermal interface is sharp and in the right location

General interface is in the wrong location

Unsplit cannot compete with Default+VOF for the ideal interface

Unsplit is more accurate for a general interface because of errors in the position for Default+VOF



General interface

Iso-thermal interface

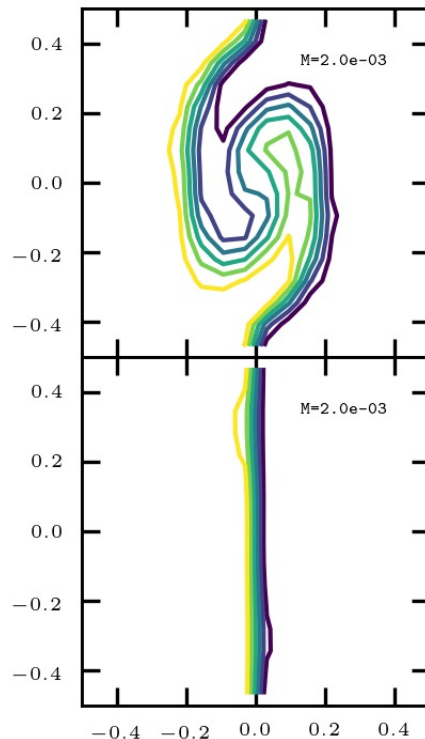
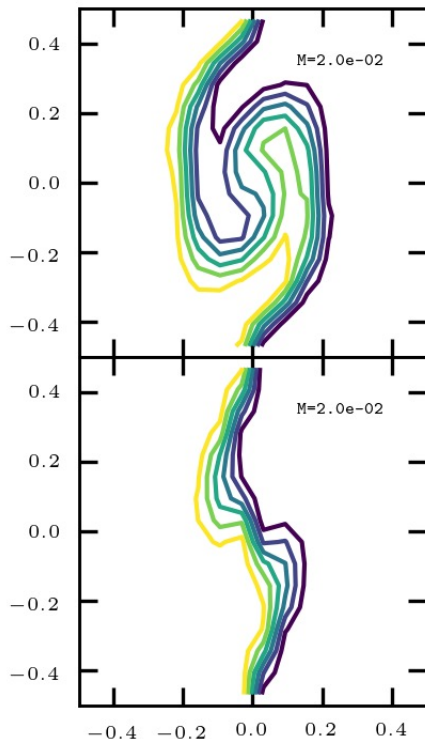
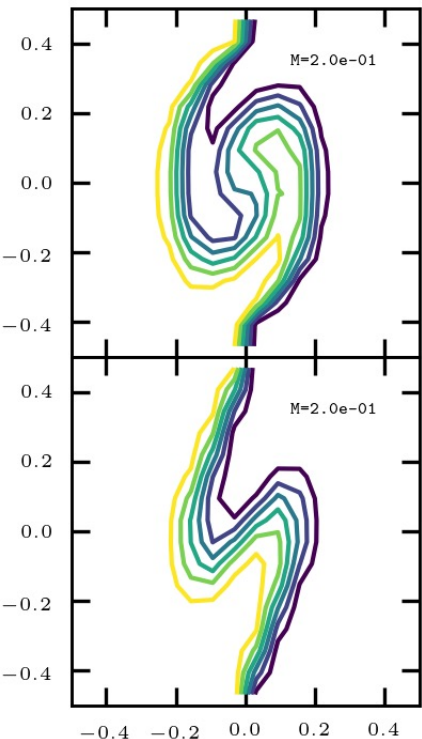
Unsplit captures fluid behavior accurately independent of Mach number

Kelvin-Helmholtz Instability

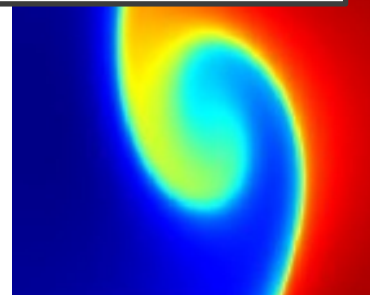
Mach 0.2

Mach 0.02

Mach 0.002



Unsplit
HLLC+LMC



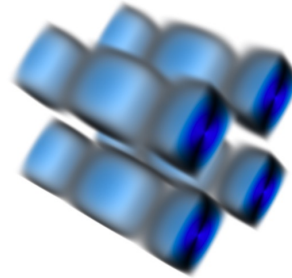
Default

**Unsplit
captures the
instability at
low Mach
number, but
Default
strongly
suppresses it**

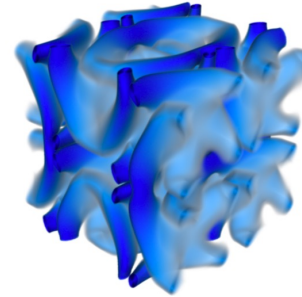
Volume fraction isocontours

Taylor-Green Vortex: A Transition to Turbulence

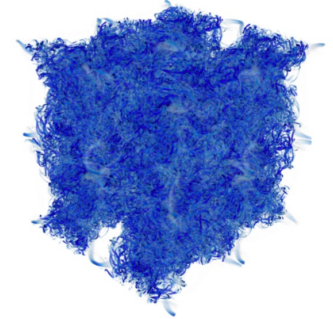
3D structured vortical flow
transitions to turbulence
that decays over time



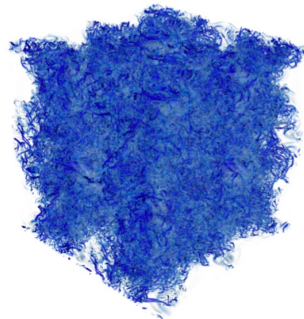
$t^* = 0$
scale 10



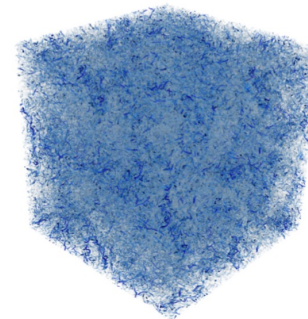
$t^* = 0.96$
scale 10



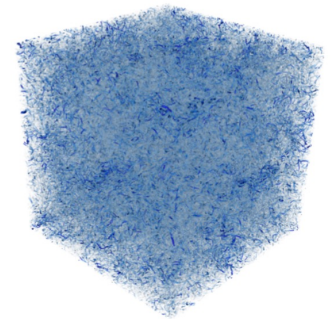
$t^* = 3.05$
scale 1000



$t^* = 3.34$
scale 1000



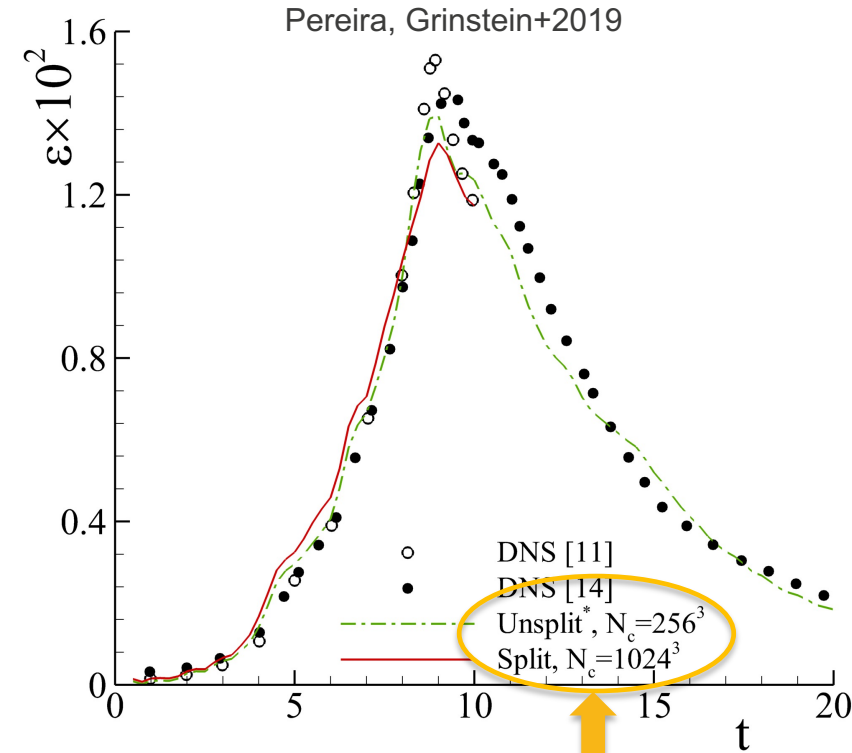
$t^* = 5.01$
scale 1000



$t^* = 8.70$
scale 250

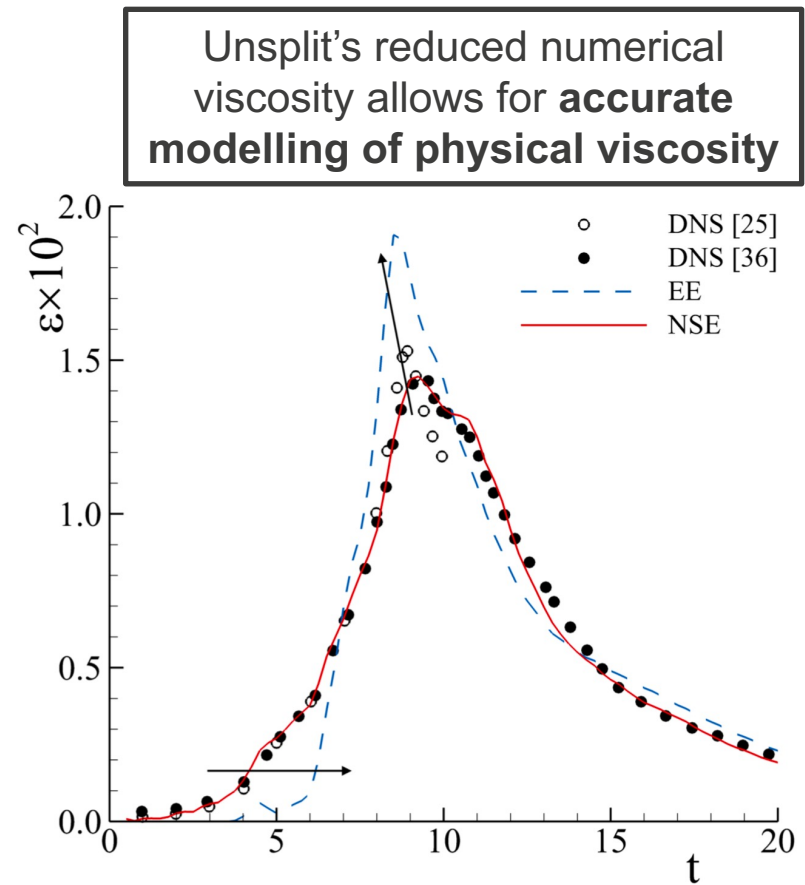
Barsukow+ 2016

Unsplit dramatically improves our ability to model turbulent flows



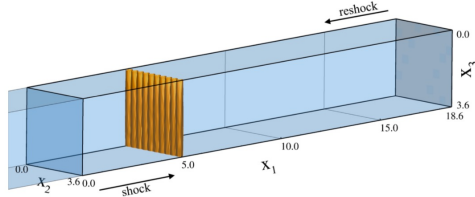
Unsplit results at 256^3
are comparable to
default results at 1024^3

$$4^4 = 256!$$



(c) EE and NSE using $N_c = 1024^3$.

Unsplit is enabling better modeling of fluid experiments



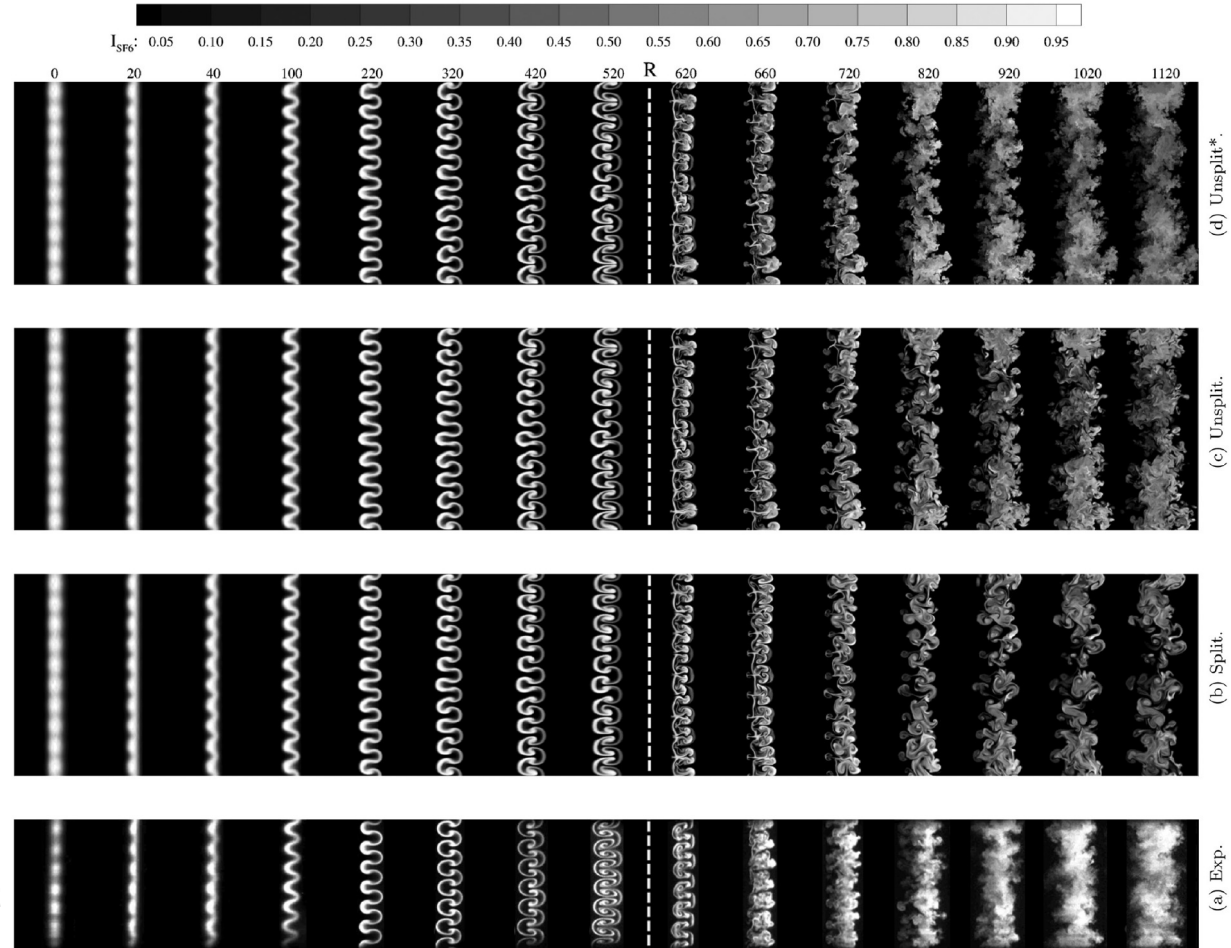
After reshock, Unsplit (especially with LMC) transitions to turbulence as in the experiment, but not Default

Unsplit
+LMC

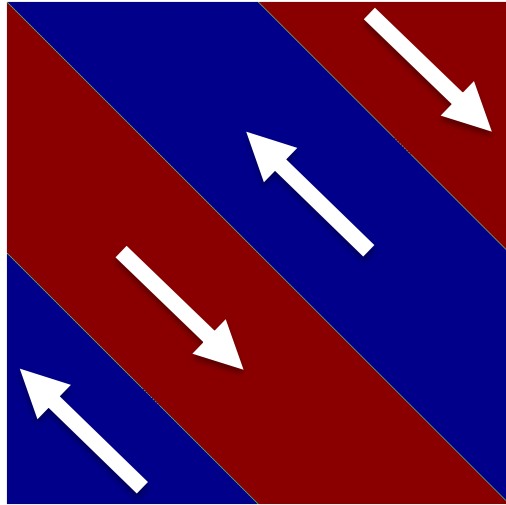
Unsplit

Default

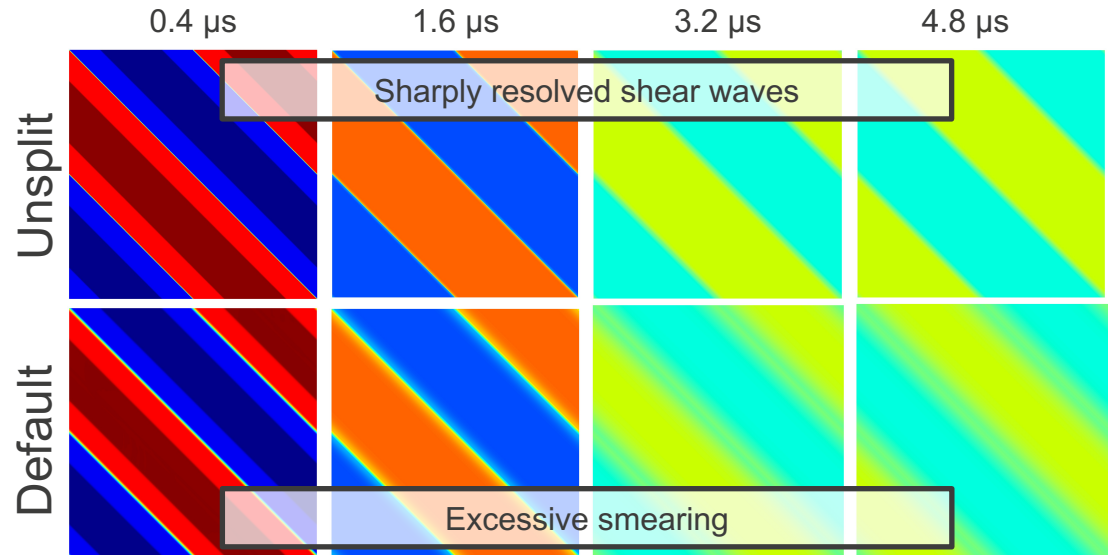
Experiment



Elastic-Plastic Shear in a Solid: Simple Solid Dynamics Problem to Quantify Accuracy



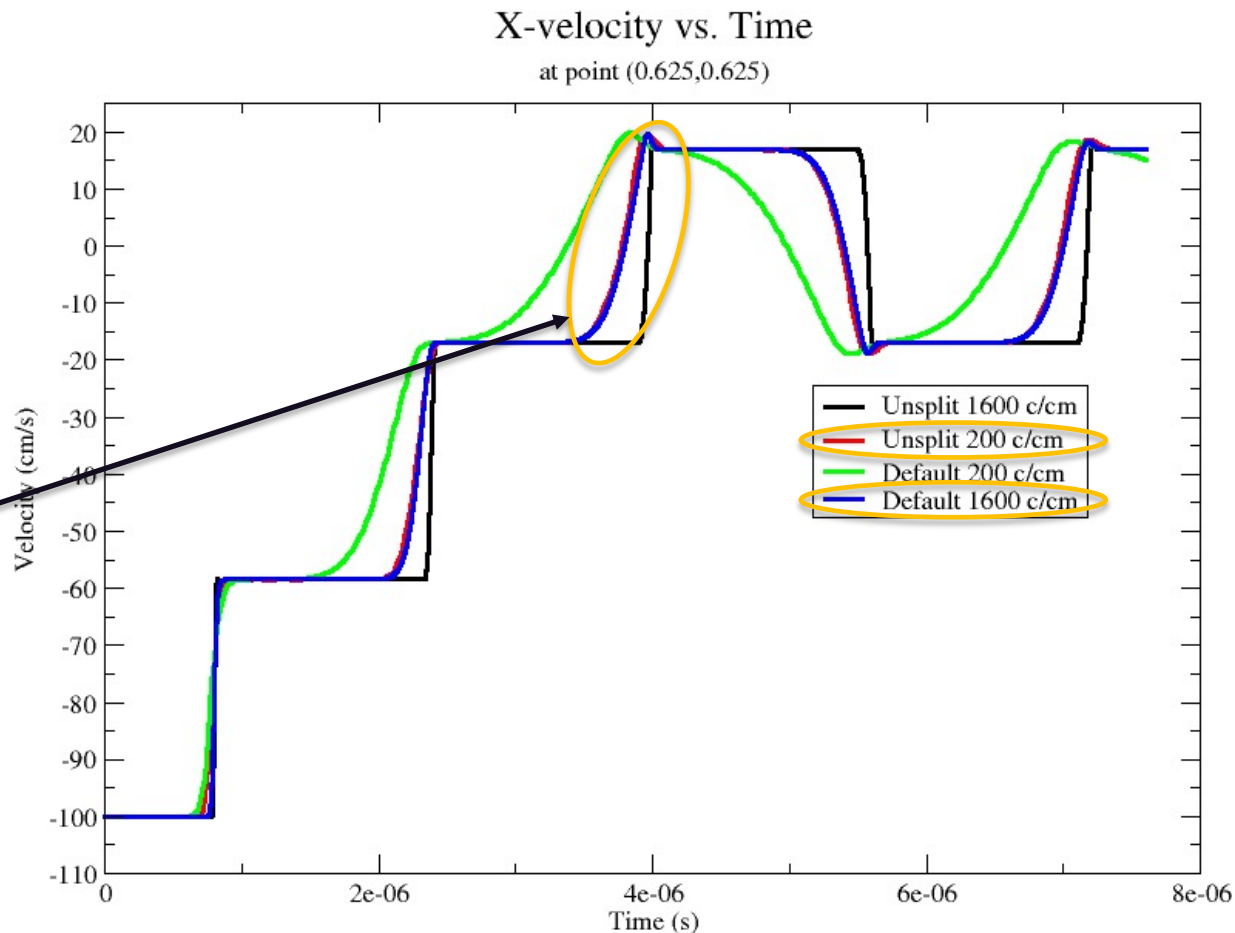
Initial Conditions



Unsplit Hydro appears to more sharply capture shear waves in solids

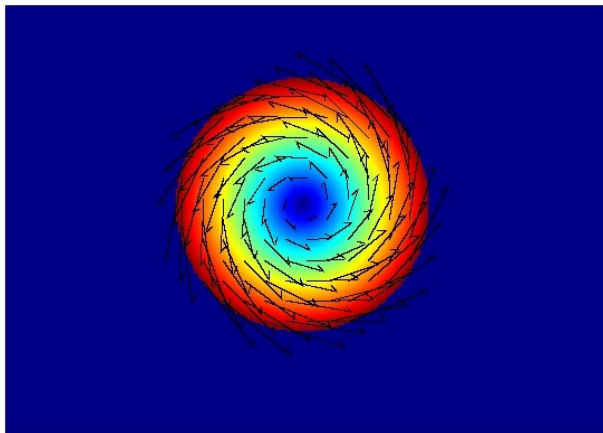
Unsplit Hydro proves dramatically more accurate

**Comparable results
with Unsplit on 8x
coarser mesh!
 $8^4=4096!$**



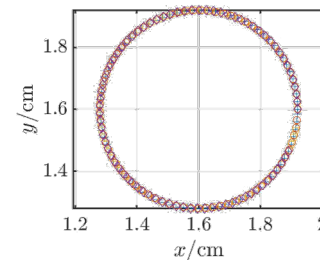
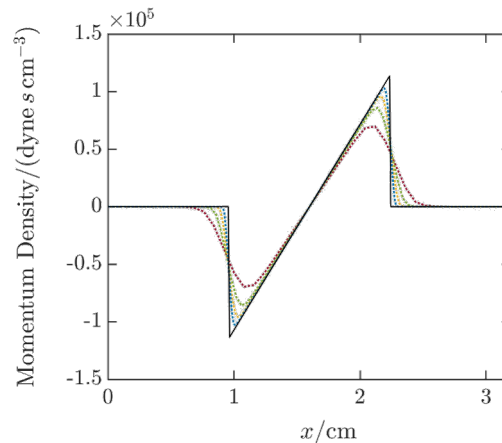
A rapidly rotating solid disk held together by tensile stresses

Initial Conditions



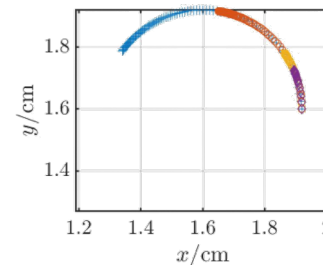
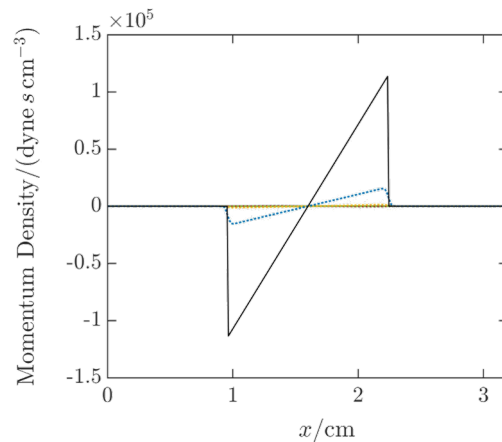
8x higher resolution in Default is still much less accurate than Unsplit

Unsplit



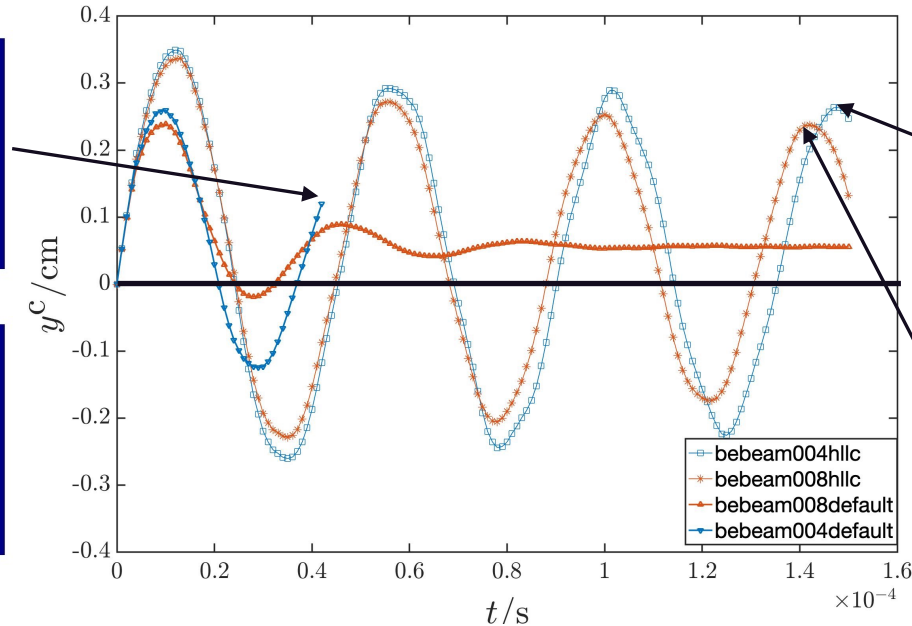
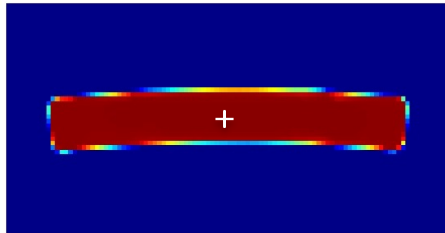
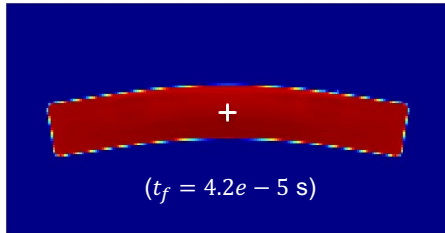
8x variation in resolution

Default

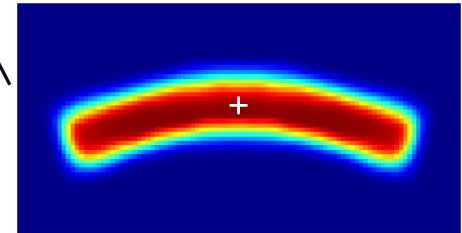
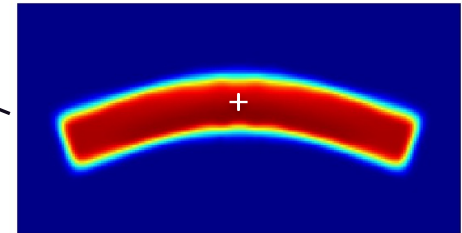


Oscillating Beryllium Beam: A simple but powerful discriminator for elastic solids

Default



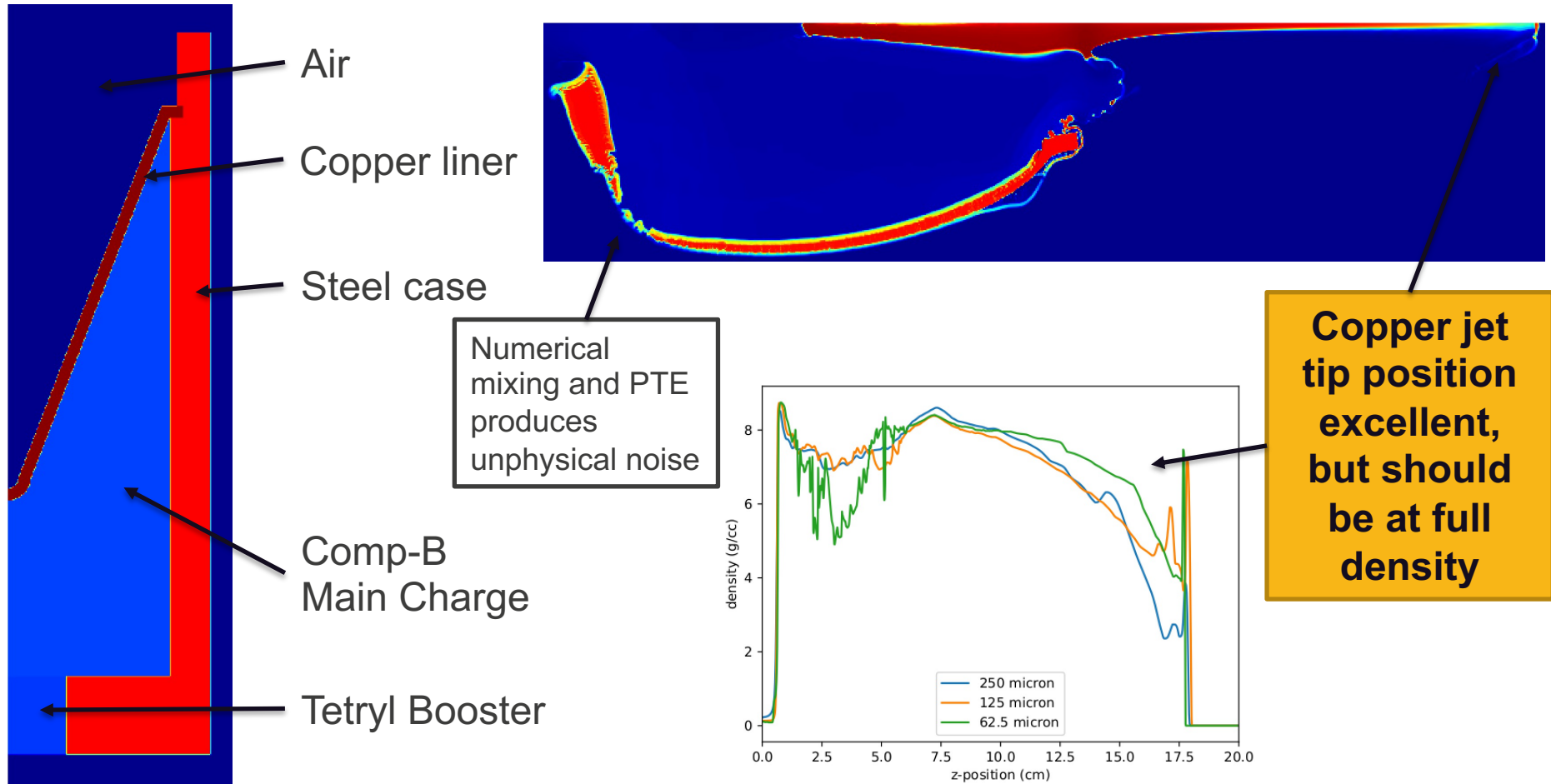
Unsplit



Unsplit dramatically improves fidelity of oscillating beam undergoing simultaneous compression, tension, and shear *despite diffuse interface*

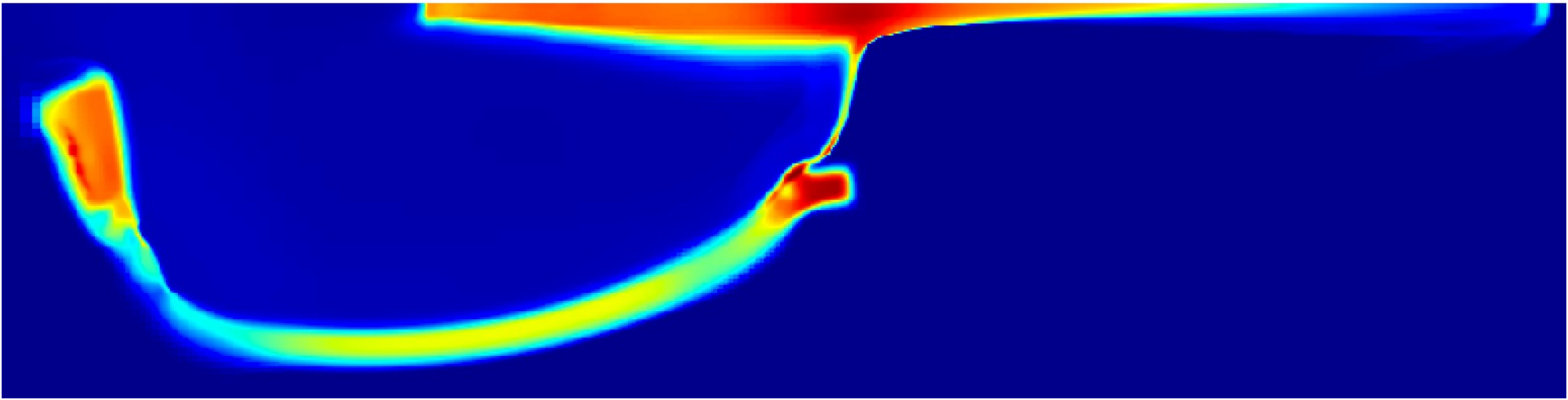
Shaped Charge:

A complex multiphysics problem that highlights gaps



Shaped Charge:

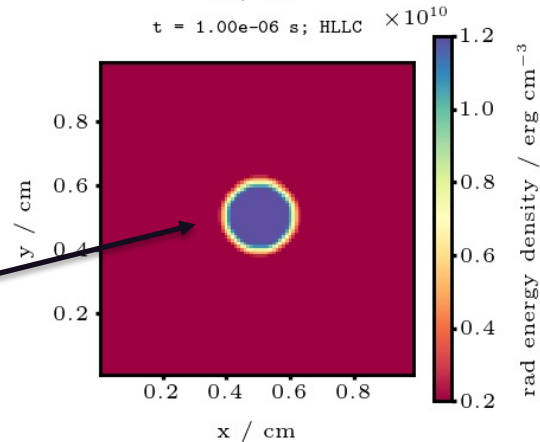
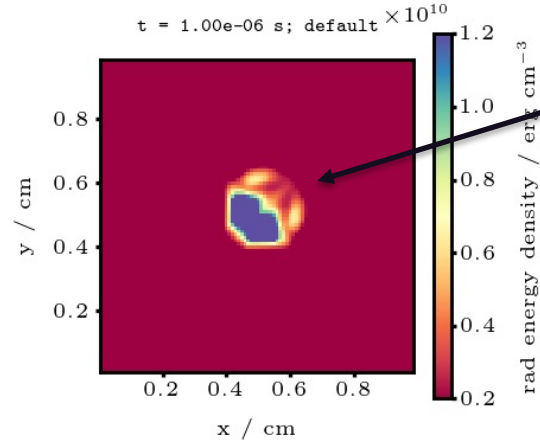
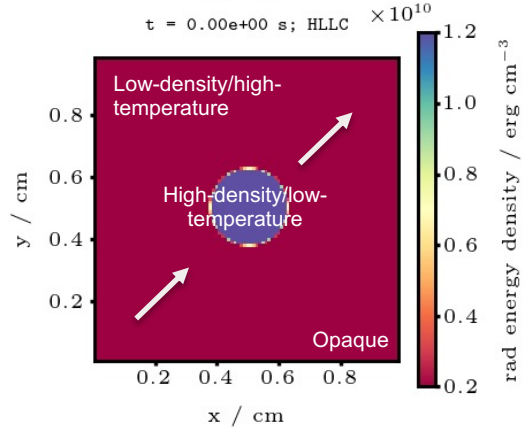
Robustness required suboptimal solver options in 3D



We were able to complete a 3D shaped charge calculation, but the more robust solver options produce excessive numerical diffusion

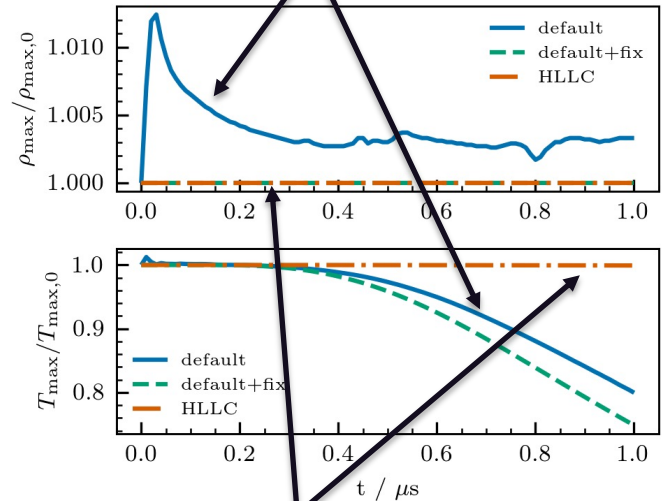
Radiation advection reveals critical importance of consistent coupling with other physics packages

Initial/Final State



**Unsplit
preserves the
shape through
advection**

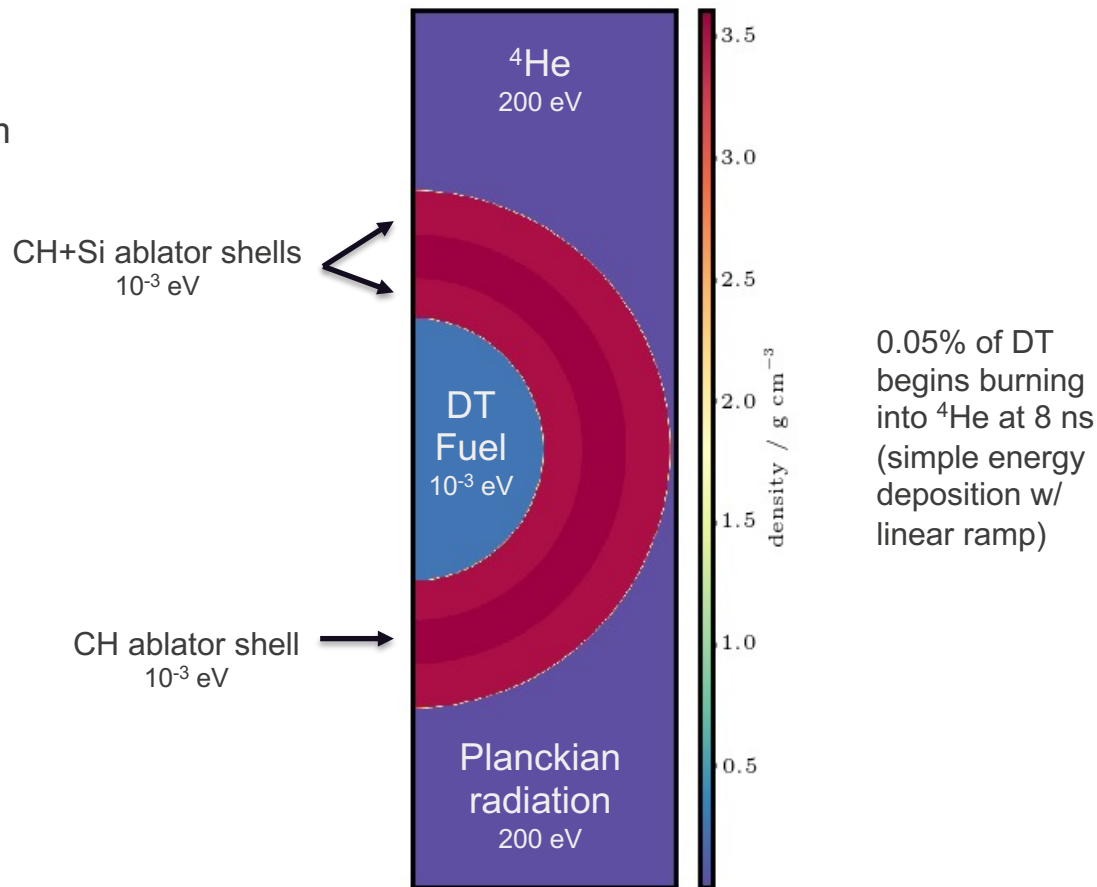
Default destroys the
shape and constancy



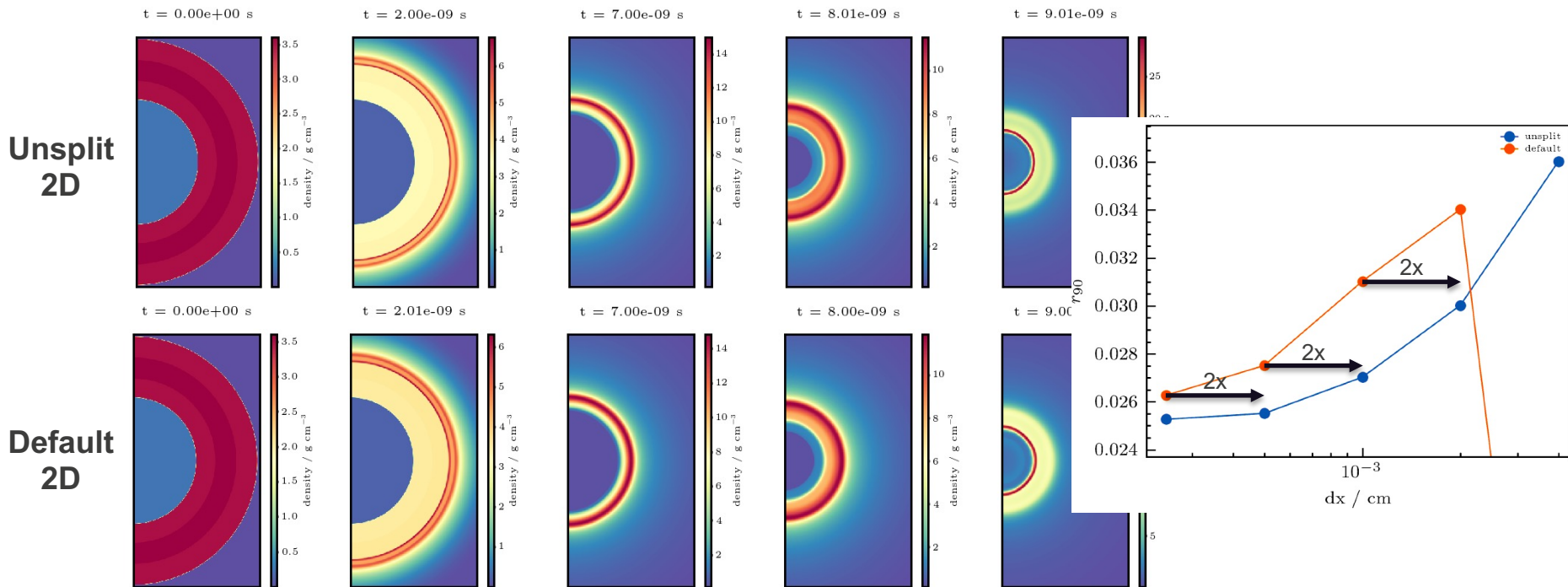
**Unsplit
preserves
constant states**

ICF Proxy stress tests HEDP capabilities

- 1d, 2d and 3d Multiphysics problem
- Hydrodynamics
- Radiation
- Multi-material
- Ionization/Isotopes
- 3T
- Electron/ion conduction
- Electron-ion coupling

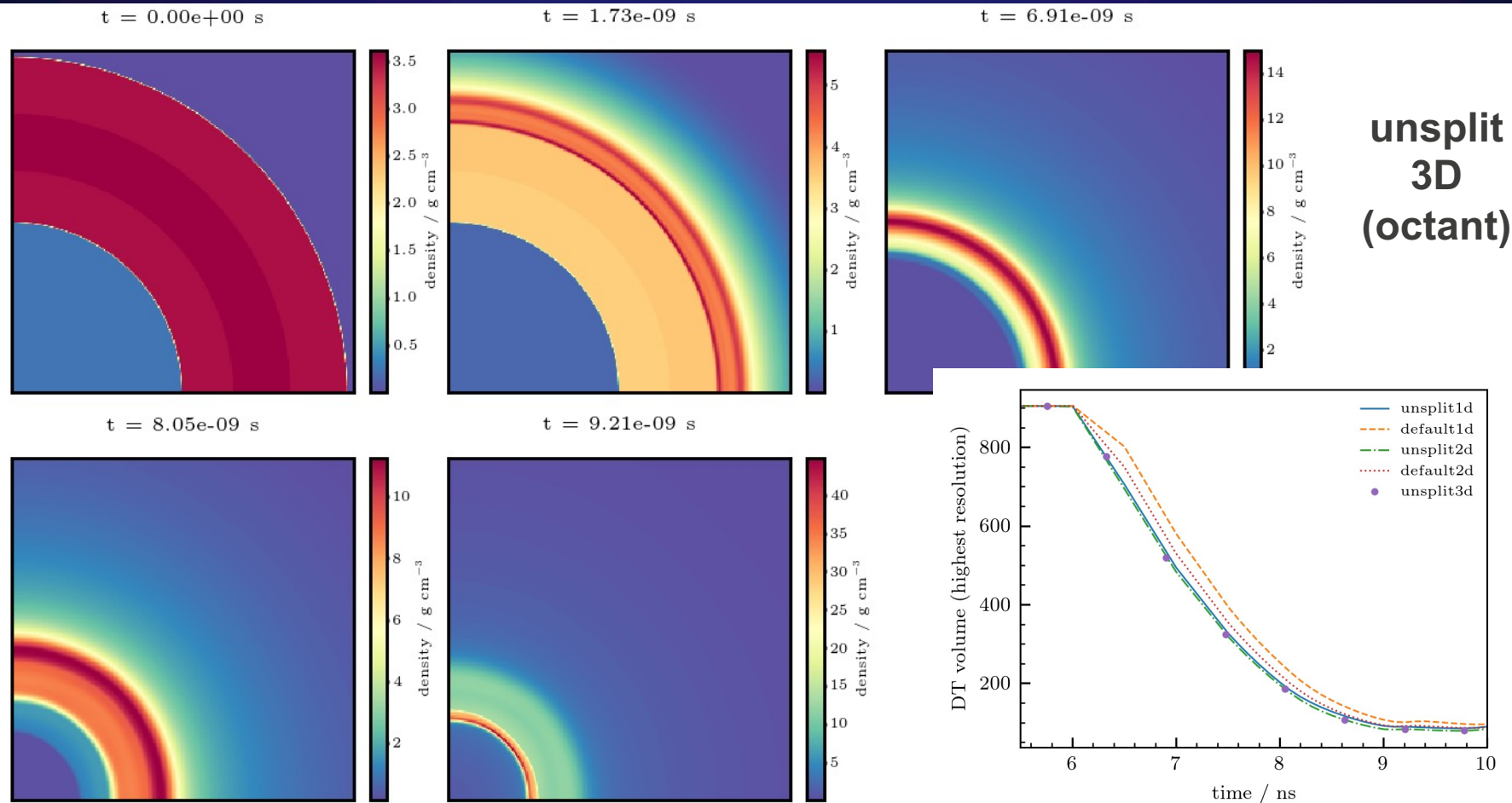


Unsplit and Default look very similar for this complex multiphysics problem



Quantitatively similar results when Default has 2x higher resolution. $2^4=16$

3D implosion remains very symmetrical and in good quantitative agreement with 1D and 2D



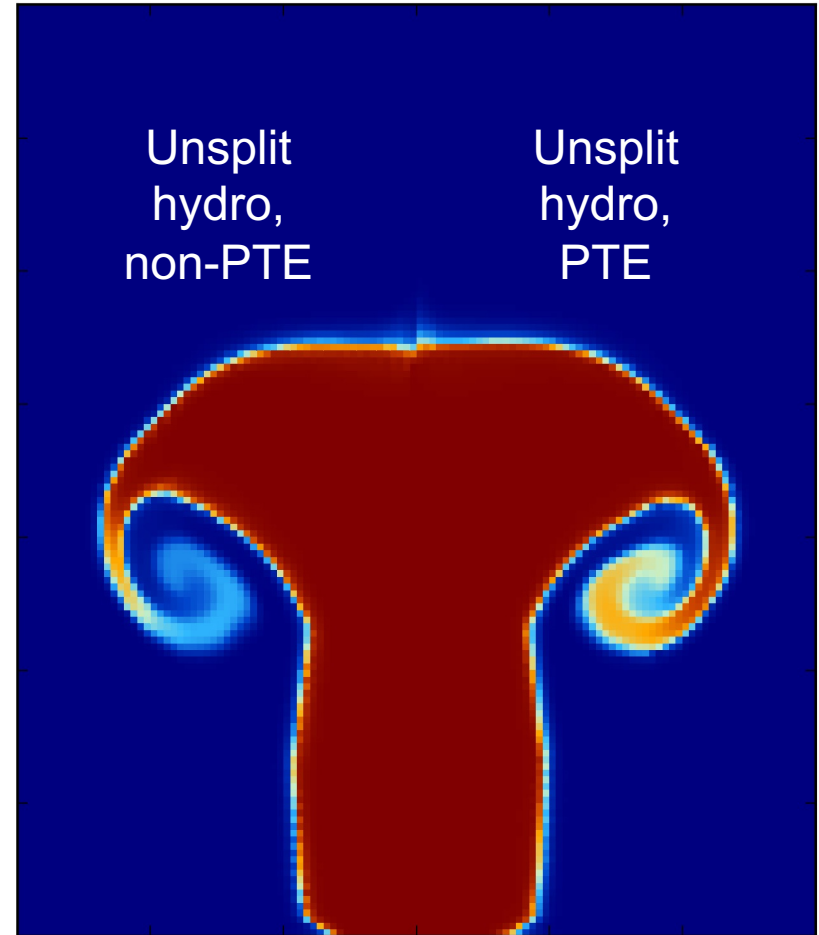
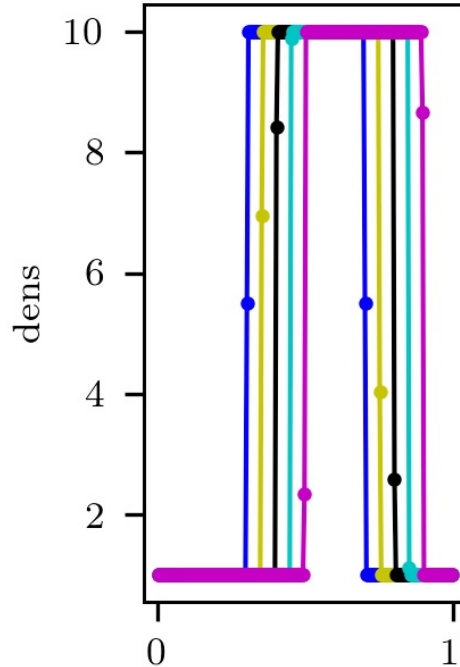
Summary Assessments

- Unsplit hydro was demonstrated to have comparable or better accuracy across a broad range of problems, with some dramatic improvements
- The shaped charge revealed some deficiencies related to numerical mixing and the PTE mixed cell closure that must be resolved before widespread adoption among users is possible
- Focus of ongoing work has three prongs
 - Introduce a method to retain sharp material interfaces
 - Relax the assumption of PTE in mixed cells
 - Production hardening

Ongoing Work in Unsplit Hydro: Sharp Interfaces and non-PTE

Unsplit hydro actually began as a
non-PTE solver

Definite progress
on sharp
interfaces in
Unsplit

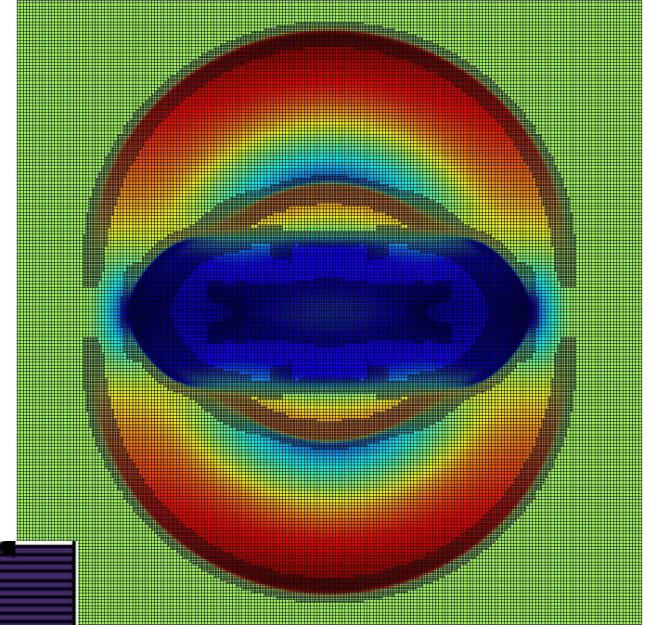
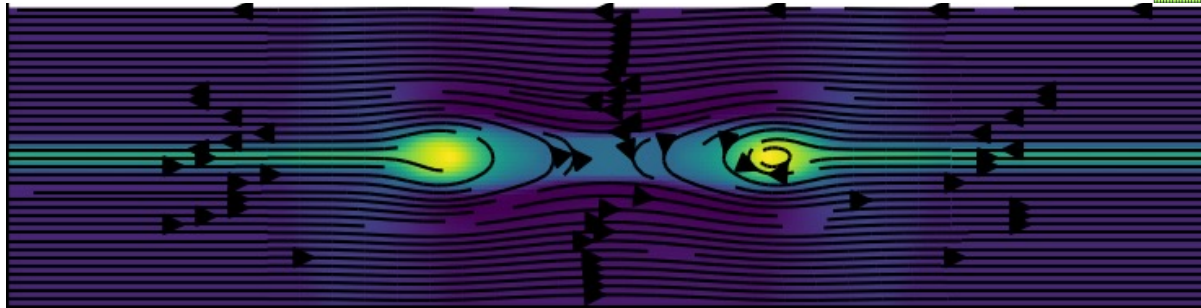


Ongoing Work Leveraging Unsplit Hydro: Resistive Magnetohydrodynamics

MHD demands a directionally unsplit method

**Unsplit is extending the physics
reach of EAP codes**

Resistive, Reconnecting Current Sheet

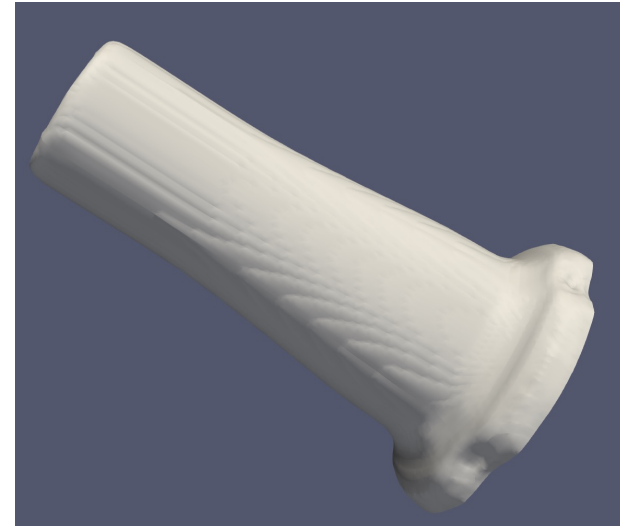
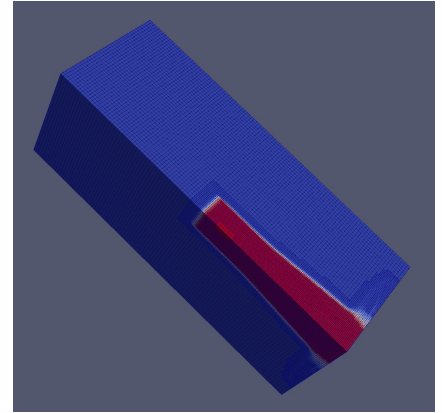


MHD Blast w/ AMR

Ongoing Work Leveraging Unsplit Hydro: Hyperelastic Material Modeling

Advanced material models often adopt a *hyperelastic* formulation, as opposed to the *hypoelastic* formulation EAP codes have always relied upon

Unsplit can naturally accommodate hyperelastic models and we have already explored a proof of principle



Thanks!